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FEDERAL COMMUNICATIONS COMMISSION
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Establishment of Rules and Policies for the Digital Audio Radio Satellite Service in the 2310-2360 MHz Frequency Band	))))))	IB Docket No. 95-91	RECEIVED SEP 14 1995 FCC MAIL ROOM

COMMENTS OF FORD MOTOR COMPANY

Ford Motor Company ("Ford") hereby comments on the Commission's proposal to establish rules and policy governing the satellite Digital Audio Radio Service ("DARS"). Ford supports the introduction of this new service which may potentially enhance the lives of the commuting public by expanding access to information, entertainment, and other communication services.

In order to foster a successful service that is desirable and useful to the public, those aspects of the proposed service impacting the performance, cost, feasibility, manufacture, and distribution of satellite DARS receivers must be given careful attention. In that context, Ford submits these comments for the purpose of facilitating service rules and policy that will create a satellite DARS system that is attuned to the needs of the consumer.

Introduction

Ford is one of the world's largest manufacturers of automobiles and related components. Its Automotive Components Division designs and manufactures audio systems, including broadcast receivers, for Ford, Lincoln Mercury, and other vehicles.

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Ford strives to provide high quality, low cost receivers that satisfy the needs and wants of its millions of customers. Ford is interested in commenting in these proceedings to help ensure that the needs and wants of those customers will be met to the fullest extent possible when satellite DARS becomes available. From Ford's perspective, the two most significant issues raised in this proceeding are 1) the provision of sufficient link margins for mobile reception and 2) standardization.

System Performance / Link Margins

Ford shares the concern expressed in paragraphs 44-46 of the NPRM that adequate link margins must be maintained for mobile reception. The existing proposals fail to demonstrate the adequacy of the proposed link margins, and Ford is concerned that the stated link margins may be inadequate. Customer expectations will be high for a satellite DARS receiver system, which will be viewed as premium, high-end systems. Given the promotion of the service as providing CD-quality audio, consumers will expect CD quality performance continuously under virtually all reception conditions.

Ford cautions against underestimating the fading effects of mobile environmental conditions upon signal reception. Attention is directed to the attached ITU-R Fact Sheet 10-11S/USA-7, dated July 13, 1995, entitled "Systems for Digital Sound Broadcasting to Vehicular, Portable and Fixed Receivers for BSS (Sound) Bands in the Frequency Range 1400-2700 MHz". As shown in Figure 5, a satellite signal received while moving over a wide range of shadowing conditions showed a dynamic range of over 35 dB. While shadowing may have the most significant consequences in urban and suburban environments since most users will be concentrated there, it should be pointed out that in Ford's terrestrial experience there are few types of geographical areas not subject to at least some significant shadowing conditions. Furthermore, all areas are subject to weather and other propagation related conditions. Thus, signal fading in the mobile environment must be addressed by providing sufficient link margin for substantially all reception areas under substantially all propagation conditions.

A study of fading and shadowing of L-band satellite transmissions at mobile receivers is described in the attached copy of E. Lutz et al., *The Land Mobile Satellite Communication Channel--Recording, Statistics, and Channel Model*, IEEE Trans. on Vehicular Technology, Vol. 40, No. 2, May 1991. pp. 375-385. This article similarly demonstrates the seriousness of the fading issue.

Inter-Operability and Standardization

Paragraphs 47 through 51 of the NPRM solicit comment concerning standardization. From the viewpoint of designing, manufacturing, and marketing receivers for a new service, it is clear that a single, open standard will greatly facilitate the likelihood of consumer acceptance of the service. In fact, it may be that wide acceptance will only be possible if such standardization is realized.

Customer acceptance of a product requires providing desirable features at a reasonable cost. The adoption of a single, open standard for broadcasting in the satellite DARS service will keep receiver costs down, minimize complexity, and encourage competition in the marketing of receivers. The single transmission and reception standard should be non-proprietary (e.g., not patented) and its details fully disclosed and available to the public. This standard should include, inter alia, criteria for coding, compression/decompression, modulation/demodulation, and protocols.

As one result of defining standards, post-demodulation signal processing (e.g., raw data processing such as compression/decompression and decoding) should be identical with potential terrestrial digital audio systems (e.g., IBOC and EUREKA-147). An Industry Advisory Committee (IAC) might prove useful and is recommended for the purpose of defining such standards.

While an open-standard approach provides great benefit to the public, it is not believed that such an approach would provide significant harm or burdens on the service providers. To a large extent, non-proprietary technologies exist which should satisfy the broadcast requirements of satellite DARS

A meaningful estimate of the cost of a receiver cannot be made at the present time since sufficient details of the transmission methods and encoding are not available. Projections must also consider feature content, the degree of integration with the rest of the audio system, performance requirements, user interface, subscription control, and many other issues. It is not possible at the present time to comment on the accuracy of others' cost estimates that are contained in the record.

Service Issues

Ford concurs that a properly implemented satellite DARS service is in the public interest provided that the service is implemented in a way to ensure proper performance in all environments, especially the mobile environment. Many public interest benefits would potentially accrue from this service, including improved audio quality, increased choices for listening, availability of data, and increased area of coverage. Although Ford is not in a position to be able to predict any possible effects satellite DARS may have on traditional AM and FM broadcasting, Ford supports the Commission's goal to ensure the continued viability of AM and FM broadcasting.

In connection with ancillary services referred to in NPRM paragraphs 29 and 30, Ford supports the granting of permission to provide broadcast of data (such as messaging, weather and road information, emergency information, etc.). A data channel capacity of about 128 kbits/sec is justified by the potential applications that have been enumerated. An open, non-proprietary standard should be required for data transmission.

Frequency Re-Use

Ford is concerned that the suggested use of cross-polarization may not provide adequate isolation for frequency re-use during mobile reception. Isolation is expected to suffer significantly due to multipath conditions. A thorough validation of feasibility for mobile reception is needed prior to adopting any rules specifying a scheme for frequency re-use.

Distribution of Receiving Equipment

In at least one proposal, it is suggested that receiver equipment would be made available to users in connection with purchasing subscriptions to the particular service. Ford believes that the public interest would best be served by a receiver/terminal equipment market that is open to all interested manufacturers and where a user may select their receiver and their service provider independently.

For subscription services, the administration of subscriber codes and activation hardware or software that may be designed into DARS receivers must be organized to support independent receiver manufacture and marketing. There should be no fees or other charges to receiver manufacturers for coordination or assignment of electronic identification numbers.

Conclusion

These comments are intended to help provide a viable service that maximizes consumer acceptance and demand for the satellite DARS service. Please contact the undersigned if further information or assistance is desired.

Respectfully submitted,

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Attachments

Voice of America / Jet Propulsion Laboratory

S-Band System

ITU-R FACT SHEET

Study Group: WP 10-11S

Question: 93/10

Date: July 13, 1995
Doc. No. 10-11S/USA-7
Ref: Rec. BO 1130
(ITU-R 10/26-E)

Document Title: **PROPOSED REVISION OF DRAFT REVISION OF REC. ITU-R BO.1130**

"SYSTEMS FOR DIGITAL SOUND BROADCASTING TO VEHICULAR, PORTABLE AND FIXED RECEIVERS FOR BSS(SOUND) BANDS IN THE FREQUENCY RANGE 1400-2700 MHz"

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Purpose/Objective: To obtain acceptance of Digital System B (the VOA/JPL receiver system) as an ITU-R recommended system for implementation by administrations, in a manner similar to what was done last year for Digital System A (the Eureka 147 system).

Abstract: The referenced document, which was most recently modified last year, contains a Note that indicates that when Digital System B is ready for further consideration, it may be recommended for implementation by administrations.

Considerable progress has been made during the past 8 months with additional design and testing of Digital System B. The tests have included satellite broadcasting with a NASA TDRS satellite and the development of an adaptive equalizer for use with terrestrial boosters. The system is also undergoing laboratory and field tests by the EIA subcommittee of digital audio radio systems. The laboratory results, at least, will be available in time for the WP10-11S meeting in September.

It is appropriate to package material, including specification summaries, that will support the desire to see this system attain the same ITU-R standing as the Eureka 147 system as far as BSS(Sound) and truly complementary terrestrial broadcasting are concerned (a hybrid system application for WP 10-11S).

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July 17, 1995

ANNEX

DIGITAL SYSTEM B

1 Introduction

Digital Sound Broadcasting System B is a flexible, bandwidth and power-efficient system for providing digital audio and data broadcasting, for reception by indoor/outdoor, fixed and portable, and mobile receivers. System B is designed for satellite, terrestrial, as well as hybrid broadcasting systems and is suitable for use in any broadcasting band.

System B allows a flexible multiplex of digitized audio and data sources to be modulated onto each carrier. This, together with a range of possible transmission rates, results in an efficient match between service provider requirements and transmitter power and bandwidth resources.

The System B receiver design is modular. A standard core receiver design provides the necessary capability for fixed and portable reception. This design is based on standard, well proven signal processing techniques for which low cost integrated circuits have been developed. Mitigation techniques, which are generally needed for mobile reception, are implemented as add-on processing functions.

In satellite broadcasting, the main impairment is signal blockage by buildings, trees, and other obstacles. Signal blockage produces very deep signal fades and it is generally not possible to completely compensate for it through link margin. Several mitigation techniques were developed or adapted during the design of the System B receiver. The System B receiver can support each of the following:

- Time Diversity (Data Retransmission) - A delayed version of the data stream is multiplexed together with the original data and transmitter on the same carrier
- Reception Diversity (Antenna/Receiver Diversity) - Two physically separated antennas/receivers receive and process the same signal
- Transmission Diversity (Satellite/Transmitter Diversity) - The same data stream is transmitted by two physically separate transmitters on separate frequencies, are received by the same antenna, then processed independently
- On-Channel Boosters (Single Frequency Network) - The same data stream is transmitted by two or more physically separate transmitters on the same frequency, then the composite received signal is processed by an equalizer

In a terrestrial system with several on-channel transmitters, as well as in a satellite system with terrestrial on-channel boosters, System B will use equalization in the receiver. This is the only time the core receiver configuration is impacted. If a receiver does not perform equalization, it must have the capability to recognize and discard the training symbols which have been inserted into the data stream.

2 System Overview

An overview of the System B design can be best obtained by examining the functional block diagram of the receiver (starting at the IF) presented in Figure 1. Core receiver functions are shown as solid blocks, while the optional functions for performing mitigation of propagation problems are shown as dashed blocks.

After the desired carrier is selected by the receiver tuning section, the signal is translated down to a fixed IF frequency.

In the core receiver, carrier reconstruction takes place in a QPSK Costas loop, and symbols are detected by a matched filter with timing provided by a symbol tracking loop. After frame sync is established, the recovered symbols are decoded and demultiplexed. The Reed Solomon decoder performs the additional function of marking data blocks which were not successfully decoded. This information is used by the audio decoder and can be used by the time or signal diversity combiner, if implemented in the receiver.

The selected digital audio source data is provided to the audio decoder while other digital data is provided to the appropriate data interfaces. Each audio encoder will have the capability of multiplexing asynchronous, program related data, with the audio data stream as shown in the figure.

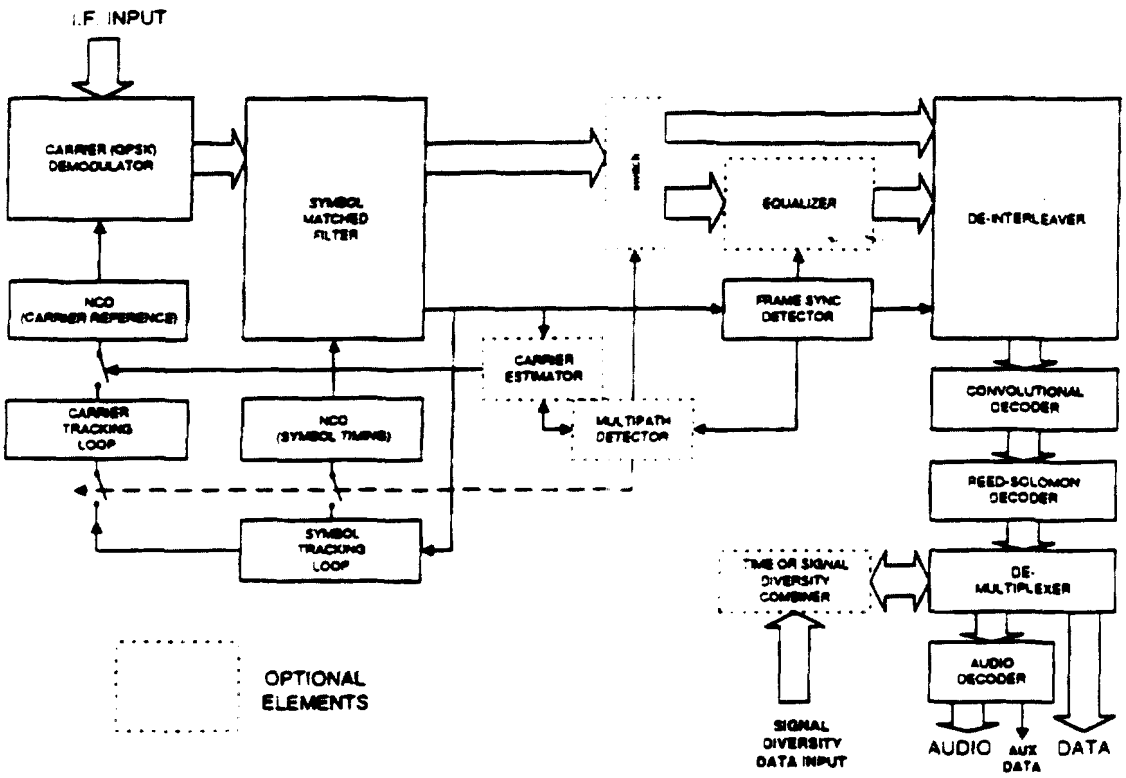

Figure 1. Receiver Functional Block Diagram

In a receiver equipped with an equalizer, the equalization can be disabled in the absence of multipath because the equalizer will introduce a nominal amount of performance degradation.

The presence of multipath can be detected automatically or the equalizer can be switched in manually if the receiver is to be operated in an area served by terrestrial transmitters. When the equalizer is operating, the carrier and symbol tracking loops are opened

Time diversity is implemented by transmitting a delayed version of a data stream multiplexed together with the original. In the receiver, these two data streams are demultiplexed and time realigned. The data stream with the fewest errors is selected for output.

Signal diversity requires the independent processing of the signal, or of different frequency signals, up to the diversity combiner. The diversity combiner then performs the functions of time alignment and selection of the most error free data stream.

3 System Description

The processing layers of the System B transmitter and receiver are described block by block, referenced to the diagram of Figure 2. Specifications are defined for each block as appropriate

3.1 Transmitter

The transmitter performs all the processing functions needed to generate a single RF carrier. The process includes multiplexing all analog audio and digital data sources to be combined onto one carrier, forward error correction encoding, and QPSK modulation

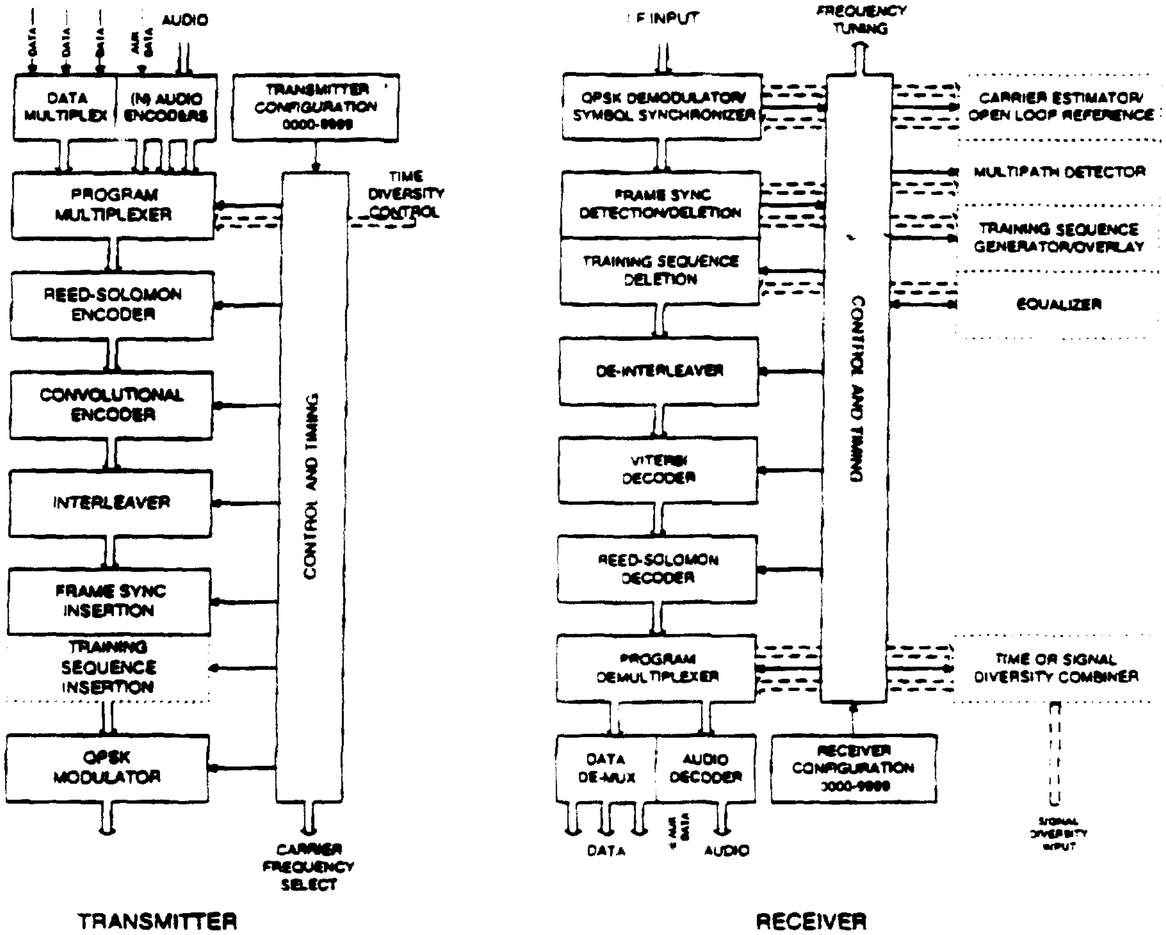

Figure 2. System B Block Diagram

3.1.1 Input Interfaces

The transmitter accepts a set of sampled analog audio signals, a set of asynchronous data sources associated with each audio source, and a set of independent synchronous data sources.

3.1.2 Audio Encoding

A number of audio encoders are provided to handle the required number of limited bandwidth monaural, limited and full bandwidth stereo, and full bandwidth five channel surround sound channels.

Each encoder also accepts an asynchronous data channel, which is multiplexed with the audio data stream. The data rate of these channels varies dynamically according to the unused capacity of the audio channel.

The output of each audio encoder is a synchronous data stream with a data rate proportional to the audio bandwidth and quality. The rate ranges from a minimum of 16 kbps for limited bandwidth monaural, to approximately 320 kbps for five channel (exact rate to be determined by MPEG committee). Audio encoder data rates are limited to multiples of 16 kbps

3.1.3 Program Multiplexing

All digitized audio channels and data channels are multiplexed into a composite serial data stream. The output data rate will range from a minimum of 32 kbps to a maximum determined by the transmitting system bandwidth and power resources. This maximum is anticipated to be in the range of 1 Mbps to 10 Mbps.

Each allowed multiplex combination of audio sources and their rates, as well as data sources and their rates, will be assigned a unique transmission identifier number. This number will be used by the receiver to set up the data rate and demultiplexing configuration.

3.1.4 Error Correction Encoding

Error correction encoding of the composite data stream consists of rate 1/2, k=7 convolutional encoding, followed by rate 140/160 Reed Solomon encoding.

3.1.5 Interleaving

A block interleaver is used to time interleave the composite data stream. The interleaver block length will be proportional to the composite data rate to provide an interleaver frame time on the order of 200 milliseconds at any data rate

3.1.6 Frame Synchronization

A PN code word is inserted at the beginning of each interleaver frame. The interleaver frame sync will also have a unique relationship with the program multiplexer frame.

3.1.7 Training Sequence Insertion

If the broadcast is to be received in an environment with on-channel repeaters, a known training symbol sequence will be inserted, with a training symbol placed every n data symbols, where n can range from 2 to 4. The presence of training symbols and their frequency will be also identified by the unique transmission identifier number.

3.1.7 Modulation

The final step in the process is QPSK modulation at an IF frequency. Pulse shaping will be used to constrain the bandwidth of the signal. From this point the modulated IF signal is translated to the appropriate carrier frequency for transmission. In a frequency division multiplex (FDM) approach, additional carriers are generated by duplicating the transmitter described above.

3.2 Receiver

After tuning to the desired carrier and translating the signal down to a fixed IF frequency, the receiver will perform the demodulation, decoding, and demultiplexing functions, as well as the digital to analog conversion of the selected audio signal.

The receiver data rate and program demultiplex configuration will be set up by inserting the unique transmission identifier number. The core receiver will be able to perform all required receive functions in a fixed or portable reception environment, where there is a stable signal with sufficient signal to noise ratio.

In mobile reception environments, where there are sufficient problems with signal blockage, the receiver will include the enhancements needed to accommodate time or signal diversity, or equalization if boosters are used.

3.2.1 Demodulation

Normally carrier demodulation takes place in a phase locked coherent QPSK demodulator, and symbols are detected by a matched filter with timing provided by a symbol tracking loop.

When equalization is used in the presence of echoes, the carrier and symbol tracking loops are opened. A FFT frequency estimator is used to set a fixed carrier demodulation reference. The symbol matched filter is sampled at twice the symbol rate and these samples are provided to the equalizer.

3.2.2 Frame Synchronization

Interleaver frame synchronization is established through cross-correlation detection of the unique frame sync word. This process also removes the ambiguity produced by QPSK modulation.

3.2.3 Equalization

In the presence of echoes, there will be several closely spaced correlation peaks in the frame sync detector output. This information can be used to automatically switch in the equalizer. The equalizer uses a locally generated training sequence whose start is based on an estimate of the position of frame sync word. A comparison of the timing of the locally generated frame sync word and the frame sync detector output allows the equalizer to adjust for any timing error between the incoming symbols and locally generated symbol timing reference.

System B uses a Lattice Predictive Decision Feedback Equalizer (Lattice PDFE) design. The leeway allowed in the time spread of all the echoes is a function of the length of the equalizer. System B performance testing employed an equalizer with 22 forward taps and 4 feed back taps. The equalizer will acquire within 100 symbol times. Equalizer length can be increased if it is necessary to compensate for greater signal delay spread.

3.2.4 Training Sequence Deletion

At the output of the equalizer, the training sequence symbols are discarded. If a receiver without an equalizer works with a signal that contains training symbols, it also must discard these symbols. This is a simple process since the position of the training symbols is known in relation to the frame sync word.

3.2.5 De-Interleaving

The deinterleaver reestablishes the original time sequence of the detected symbols, as it existed in the transmitter prior to interleaving.

3.2.6 Error Correction Decoding

A Viterbi decoder, followed by a Reed Solomon decoder, reduces the detected symbol error rate and converts the symbols back into data bits. If the Reed Solomon decoder is unable to remove all the errors in a data block, it marks the data block as bad. This indication can later be used by the diversity combiner to select the better signal, as well as by the audio decoder to control audio output squelching.

3.2.6 Program Demultiplexing

At this point the composite data stream is demultiplexed into separate digital data streams and the desired audio data stream is selected and routed to the audio decoder.

If time diversity is used, the program demultiplexer separates the real time and delayed version of the data stream, and sends them to the diversity combiner for selection of the least corrupted data.

If an independent receiver is used for diversity reception, this is the point where the more robust output data is selected.

3.2.7 Audio Decoding

The audio decoder converts the selected digital audio channel to analog. It also demultiplexes the auxiliary data channel and provides the data to the appropriate output interface.

3.2.8 Output Interfaces

Output interfaces consist of the selected audio channel and selected data channels. The data channels can drive displays in the receiver, or be routed to special purpose displays in data casting applications. Since more than one audio channel may exist in a transmission multiplex, the channels not selected for listening can be recorded for later playback.

4 Performance

The performance of System B is referenced to a set of standardized channel models: an additive white Gaussian noise (AWGN) channel; a satellite model for a single satellite signal; and a multiple (single frequency) signal model which can represent a satellite signal with terrestrial boosters or a purely terrestrial network.

4.1 AWGN Channel

A clear line-of-sight satellite link can be approximated with a AWGN channel. There is very little multipath (Rician k factors generally below 10 dB) at satellite elevation angles above 20 degrees.
The measured performance of a System B receiver over a AWGN channel is shown in Figure 3. Also shown are some comparisons between theory, simulation, and measurement results.

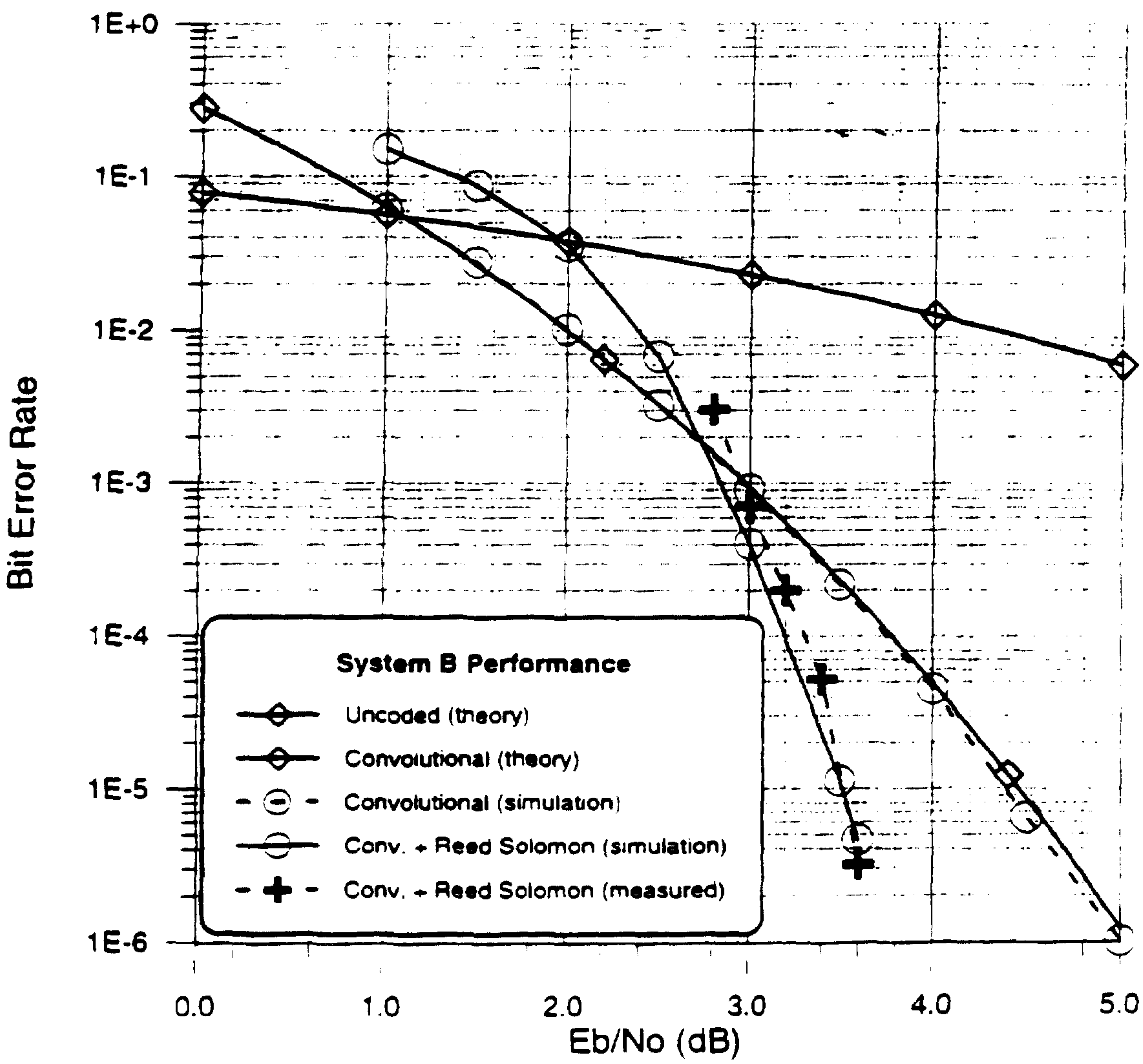

Figure 3. System B Performance in AWGN

Since System B can use several independent carriers in a FDM mode, carrier spacing is of interest. Figure 4 shows the measured performance degradation as a function of adjacent carrier spacing. Spacing is given as a ratio of carrier separation in Hz, to transmitted symbol rate in symbols per second. In System B the symbol rate is equal to the data rate times the Reed Solomon overhead of 160/140, times the training symbol overhead.

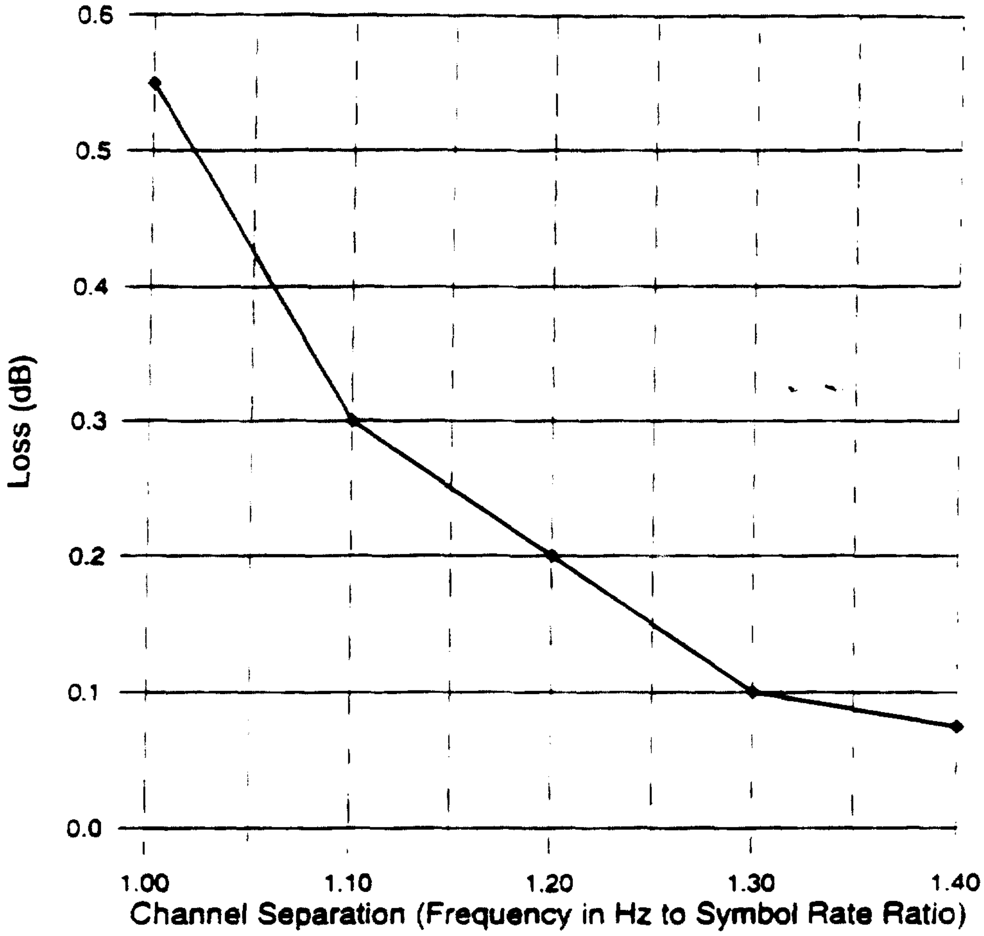

Figure 4. Performance Degradation as a function of Carrier Spacing

4.2 Satellite Channel

The satellite channel changes for mobile reception because the satellite signal is randomly blocked by buildings, trees, and other obstacles. In order to evaluate System B performance under mobile reception conditions, a model was established through a satellite signal measurement over a specific test course in the Pasadena, California area. The test course takes 45 minutes to cover and includes a variety of reception conditions, including open, moderately shadowed, and severely shadowed segments. The satellite signal measurement was a narrow band measurement which yielded a dynamic range of over 35 dB. A time plot of the model is shown in Figure 5. Figure 6 summarizes the statistics of the signal measurement.

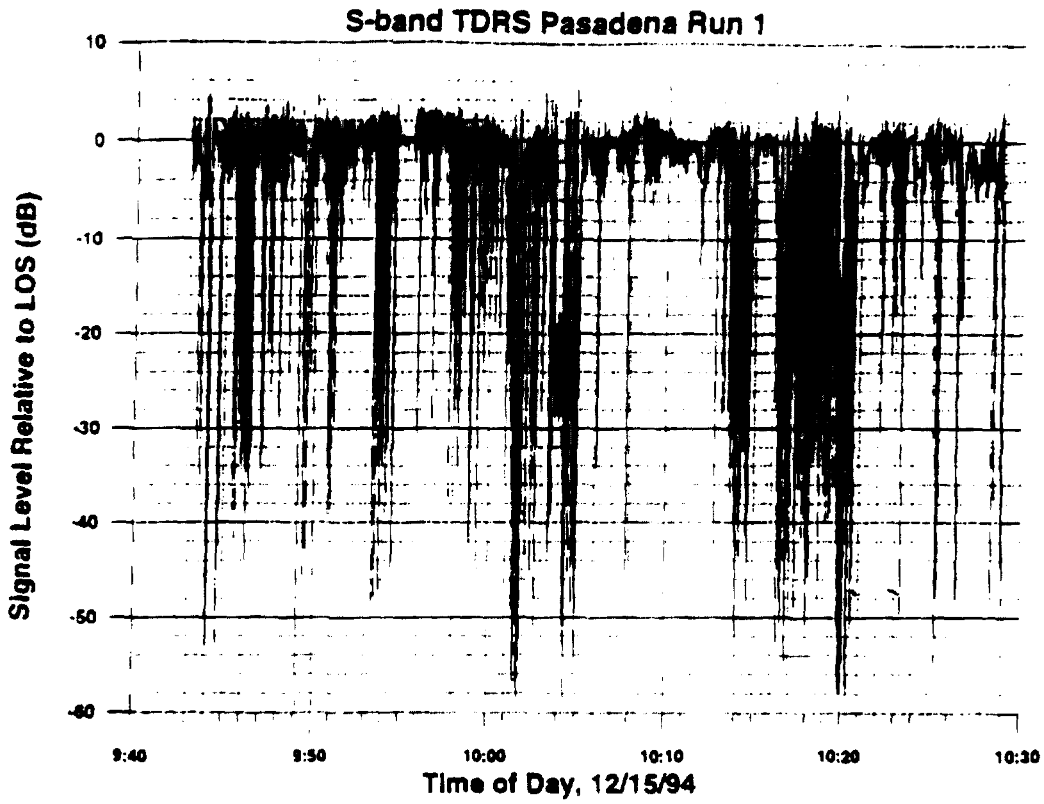

Figure 5. Satellite Channel Model

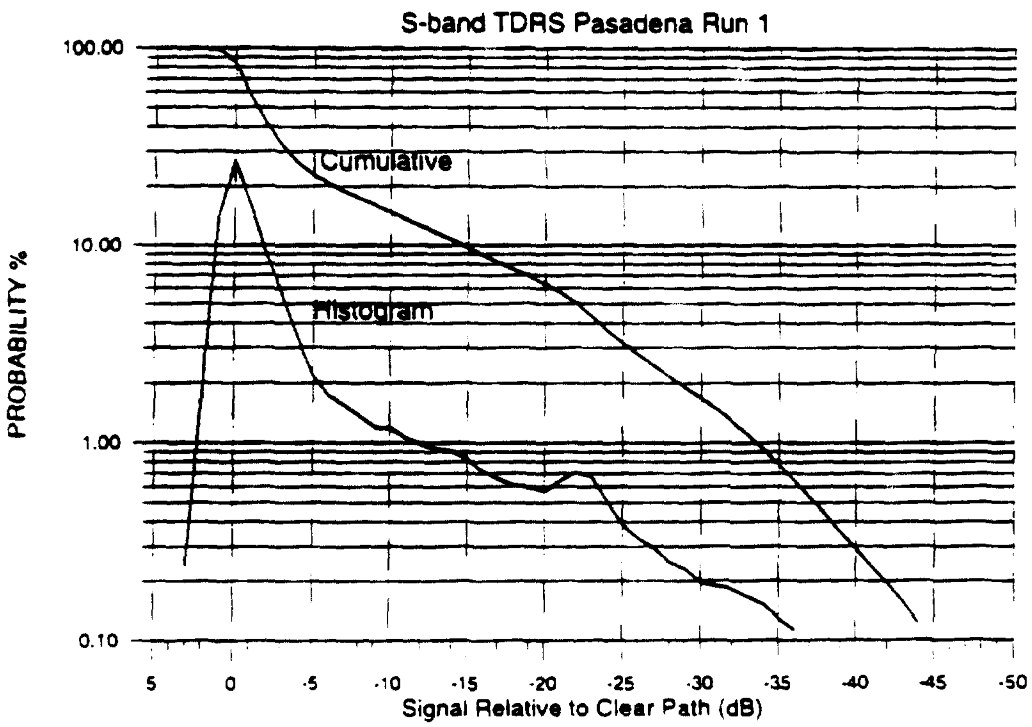

Figure 6. Satellite Channel Model Statistics

4.2.1 Time Diversity

If only a single satellite signal is available, an effective mitigation technique is time diversity. A delayed version of a data stream is multiplexed with the original data stream, with the expectation that at least one version will not be blocked. The receiver realigns the two data streams in time and selects the one with the fewest errors. This can be done on the basis of the Reed Solomon decoder error indication.

Retransmission of the data stream adds a 3 dB penalty to the system, however it can be shown that this is more effective than a 3 dB increase in link margin. Figures 7 and 8 show the effectiveness of time diversity, using the Pasadena channel model. Figure 7 shows the joint probability of a fade exceeding a range of link margins, averaged over all the model reception conditions. Note that most of the improvement occurs within about 4 seconds of delay. Figure 8 shows the joint fade probabilities, for a fixed 10 dB margin, separated by different reception conditions.

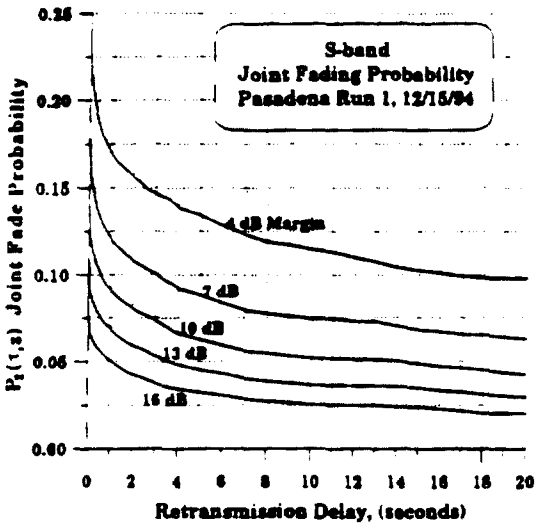

Figure 7. Joint Fade Probability vs. Link Margin

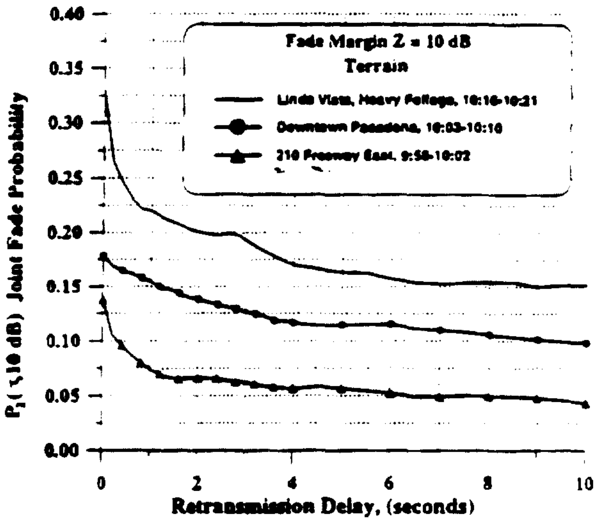

Figure 8. Joint Fade Probability vs. Environment

4.2.2 Satellite Diversity

More than one satellite can be used to broadcast the same data stream, using separate frequencies and separate receivers for each signal. The expectation with this technique is that at least one of the signals will not be blocked because of the difference in direction from the receiver to the satellites.

The effectiveness of satellite diversity, as with time diversity, depends on the local geometry of the obstacles producing the signal blockage. Photogrammetric techniques have recently been applied to obtain the statistics on the effectiveness of satellite diversity. These techniques involve taking photographic images with a fish eye lens camera pointed at zenith, then analyzing them to determine the percentage of sky that is clear, shadowed, or blocked. Satellite position can be overlaid on these images to give an assessment of diversity gain over a specific location or path.

4.3 Single Frequency Network

A method for getting a satellite signal into very difficult reception areas is to use a network of on-channel terrestrial retransmitters. System B uses equalization to work in this signal environment. The only restriction in the use of equalization is that each signal is delayed at least one half symbol from every other. There is no restriction as to how close boosters are to each other if different delays are incorporated in each one The maximum delay between boosters will be set by the number of stages incorporated into the equalizer.

4.3.1 Channel Models

Two signal models were set up to evaluate the performance of the System B equalizer. In addition. the effectiveness of signal reception diversity was evaluated

The first is a Rician model, with one half the power in a direct signal component. and one quarter of the power in each of two Rayleigh components. The Doppler spread on the Rayleigh components was set to +/- 213 Hz, which corresponds to a vehicle speed of 100 km/hr, at a carrier frequency of 2.3 GHz. The transmission rate is 300.000 symbols per second. Eb/No is defined on the basis of total signal power and includes the effect of the training sequence overhead.

The second is a Rayleigh model. with three equal power Rayleigh signal components

4.3.2 Equalizer Performance

Initial trade-offs and performance evaluation was accomplished using a "short-cut" simulation approach that assumed signal time separation in integral symbols times and perfect symbol timing recovery The results are shown in Figure 9. The bit error rate is uncoded error rate, before the Viterbi and Reed Solomon decoding. An uncoded error rate of 1 in 10E2 will be reduced to 1 in 10E6 by the decoding process.

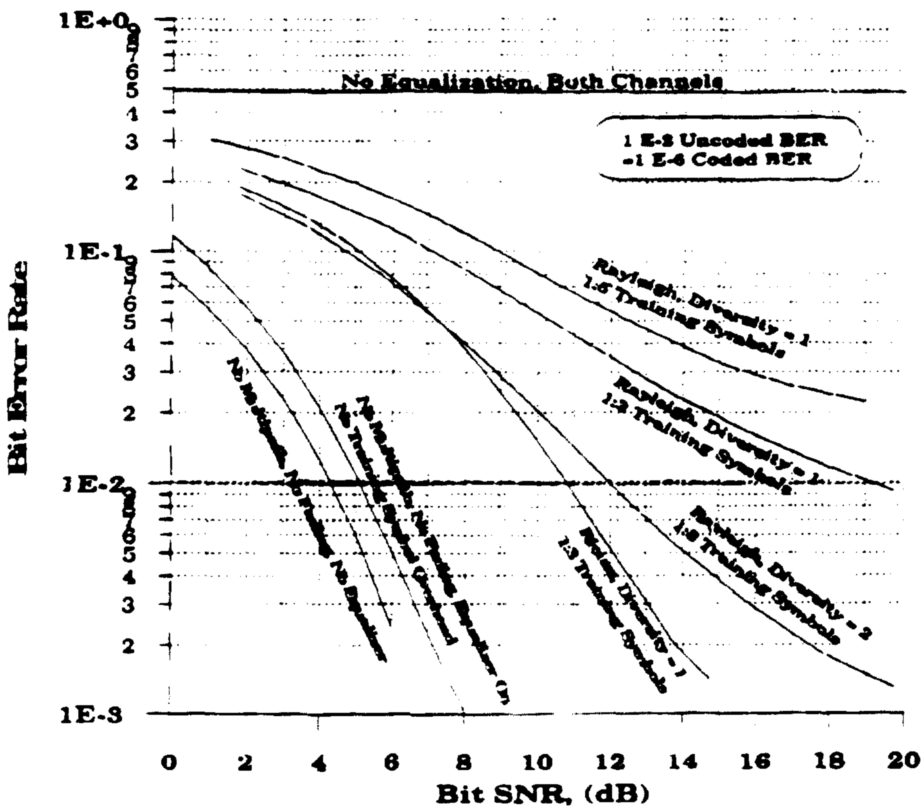

Figure 9. System B Ideal Equalizer Performance

Figure 10 shows performance obtained with full scale simulation, including open loop operation of the carrier demodulation and symbol timing loops.

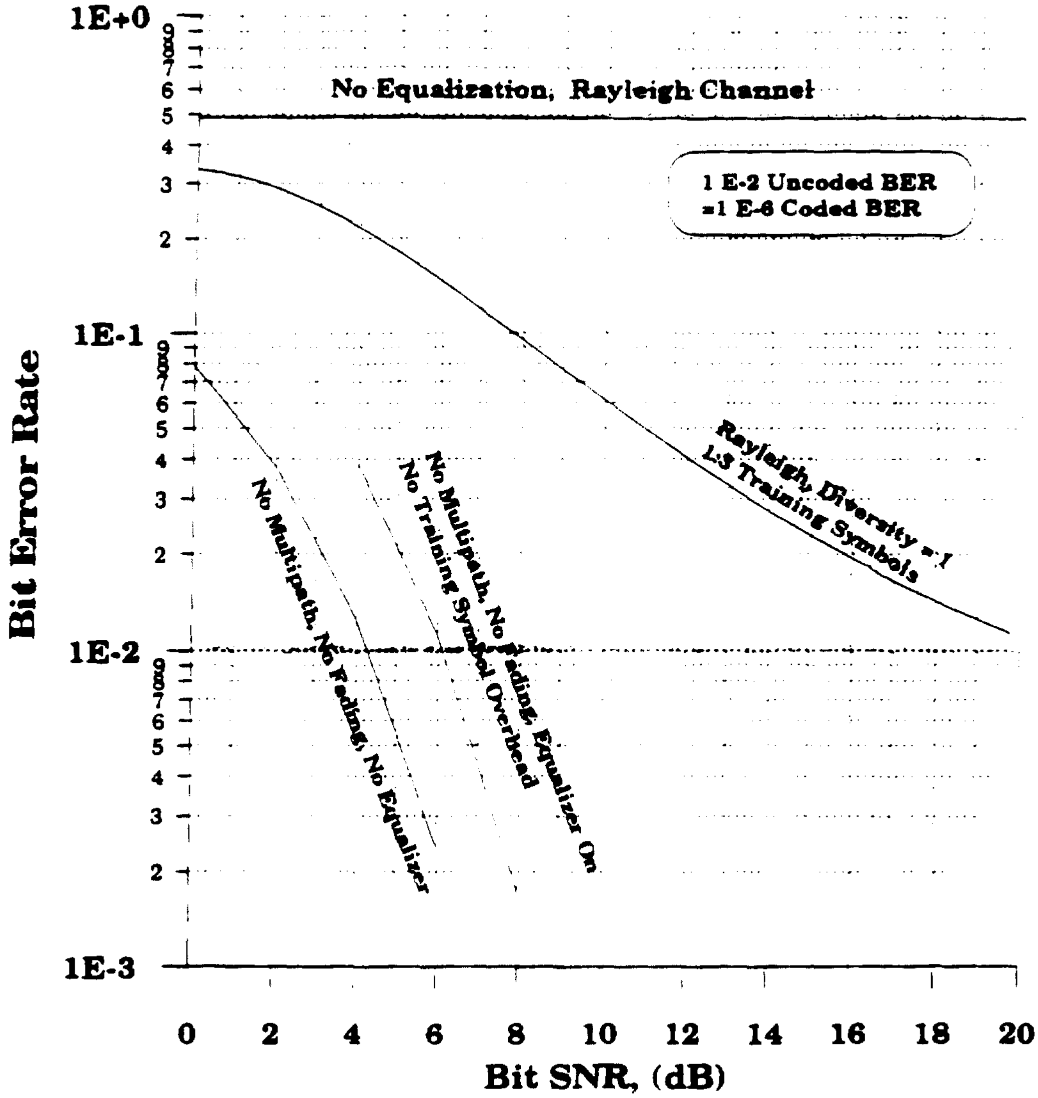

Figure 10. System B Equalizer Performance

The Land Mobile Satellite Communication Channel—Recording, Statistics, and Channel Model

Erich Lutz, Daniel Cygan, Michael Dippold, Frank Dolainsky, and Wolfgang Papke

Abstract—**The communication channel between the MARECS satellite at 26° W and a cruising van was measured and recorded in European areas exhibiting satellite elevations from 13 to 43 deg. Different environments and mobile antennas were tested. Results of an extensive statistical evaluation include spectra of the fading amplitude, probability density, and distribution of the received signal power, as well as the percentage of time for fade and nonfade periods. Based on the physical phenomena of multipath fading and signal shadowing, an analog model of the land mobile satellite channel is developed which can readily be used for software and hardware fading simulation. The most important parameter of this model is the time-share of shadowing A, ranging from less than 1% on southern highways to 89% in the city of Stockholm. The Rice-factor c, which characterizes the channel during unshadowed periods, can vary from 3.9 to 18.1 dB. For analytical purposes the land mobile satellite channel can be represented by a digital two-state Gilbert–Elliott model. For DPSK modulation with a 10 dB signal-to-noise ratio in the satellite link, the mean bit error probability in the unshadowed channel state is typically in the range of 10^{-4}–10^{-2}, while it is around 0.3 in the shadowed channel state. With regard to data transmission, block error probability density (probability of m errors occurring in a block of n bits), error gap distribution, and block error probability are discussed. The results show good agreement between the recorded channel and the channel models. Moreover, if the transmission scheme is suitably adapted to the channel behavior, reliable and efficient data transmission via the land mobile satellite channel should be achievable.**

I. Introduction

FOR some years many activities aimed at the introduction of land mobile satellite communication services have been undertaken by different organizations all over the world. For example, MSAT-X of NASA, U.S. [1], [2]; MSAT Program of DOC, Canada [3]; experimental program of Japan [4]; Mobilesat of AUSSAT, Australia [5]; and PRODAT of ESA [6]. Finally, INMARSAT is expanding into the area of land mobile services using the operational maritime standard-C system as an initial base [7]. Field tests are also being conducted on satellite paging [8].

Satellite communications with land mobile terminals suffer from strong variations of the received signal power due to signal shadowing and multipath fading. Shadowing of the satellite signal by obstacles in the propagation path (buildings, bridges, trees, etc.) results in attenuation over the total signal bandwidth. This attenuation increases with carrier frequency, i.e., it is more marked at L-band than at UHF. For low satellite elevation the shadowed areas are larger than for high elevation. Multipath fading occurs because the satellite signal is received not only via the direct path but also after being reflected from objects in the surroundings. Due to their different propagation distances, multipath signals can add destructively resulting in a deep fade.

Therefore, for all types of land mobile systems, the communication link between the satellite and the mobile terminal is the most critical part of the transmission path and limits the performance of the total system. The introduction of a judicious fade margin into the link budget has substantial consequences for the system cost. The link availability determines the achievable throughput efficiency and the resulting message delay. Furthermore, the time-varying behavior of the land mobile satellite link must be considered when choosing a modulation scheme as well as when designing channel access and error protection methods [9]. Also, carrier recovery, bit timing, and frame synchronization have to be adapted carefully to the channel behavior. For these reasons it is essential to thoroughly investigate the characteristics of the land mobile satellite link. Propagation measurements of the L-band land mobile link have been carried out in different geographical areas and different types of environments in the U.S. and Canada [10]–[12].

From 1984 to 1987 DFVLR[1] performed several series of channel recording experiments in Europe. These tests were narrow-band measurements at a single frequency, representing the channel within its coherence bandwidth [13]. The unmodulated test carrier was transmitted from the ESA ground station in Villafranca, Spain, and relayed by the geostationary satellite MARECS at L-band (1.54 GHz). The test carrier was transmitted right-hand circularly polarized with an EIRP of 28 dBW. The receiver signal-to-noise ratio was typically 25–30 dB for a 50-Hz receiver bandwidth. The L-band carrier was received by a cruising van equipped with different antennas according to Table I. All antenna patterns were horizontally symmetrical to avoid antenna steering. The antennas with toroidal patterns exhibit vertical selectivity.

The measurements were conducted in areas with different satellite elevations: Stockholm (13°), Copenhagen (18°),

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[1] In the beginning of 1989 DFVLR was renamed DLR.

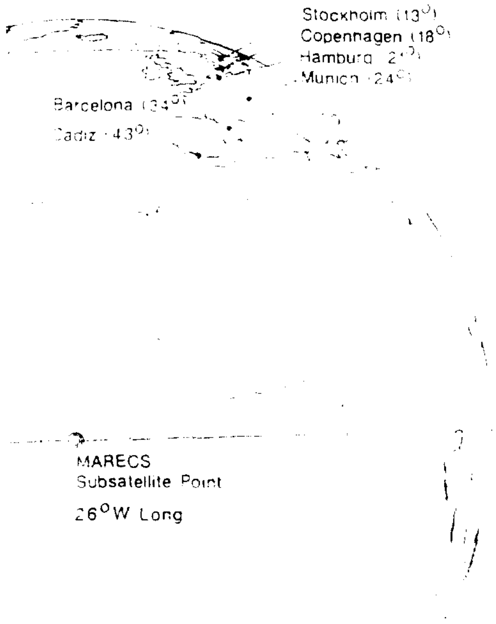


Fig. 1. Areas of land mobile channel measurements as viewed from MARECS

TABLE I
ANTENNAS USED FOR LAND MOBILE SATELLITE CHANNEL RECORDINGS

Antenna	Antenna Type	Nominal Gain	Antenna Pattern
C3	Conical spiral	3 dBi	Hemispherical
M2	Microstrip	2 dBi	Broad toroidal
D5	Drooping crossed dipole	5 dBi	Toroidal
S6	Cylindrical slot	6 dBi	Toroidal

Hamburg (21°), Munich (24°), Barcelona (34°), and Cadiz (43°). Fig. 1 shows the measurement areas as viewed from the MARECS satellite. The test courses were carefully selected to represent different types of environments (city, suburbs, rural roads, highway) and to comprise a mixture of cruising directions. A recording experiment typically lasted from 30 to 60 min.

The received carrier was downconverted to baseband, and its inphase and quadrature components were continuously recorded on magnetic tape. The recorded time-varying behavior of the land mobile channel can be reproduced in amplitude and in phase for stored channel tests [14], and for statistical analysis.

In Section II, results of the statistical evaluation of the recordings are presented. In addition to fade depth statistics, distributions of fade durations and non-fade durations are given. In Section III, two types of models for the land mobile satellite channel are developed. The analog channel model not only yields an analytic approximation of the received signal power distribution but also models the time-dependent behavior of the complex fading process and the shadowing. A digital channel model reproduces the statistics of the bit error sequence. In Section IV, block error statistics are used to compare the behavior of the channel models and of the recorded channel.

II. Statistical Evaluation of Channel Recordings

After an initial quick-look test, the analog tape recordings were digitized and transferred to a mainframe computer for

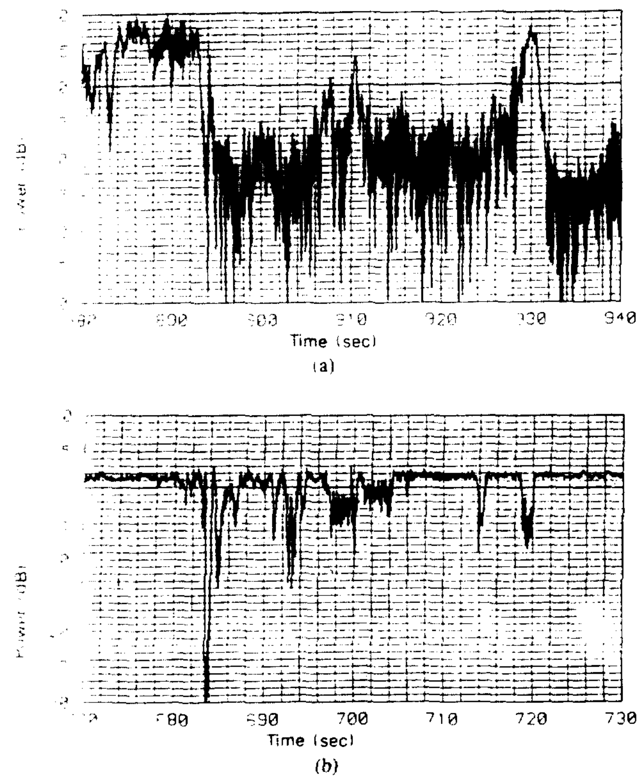


Fig. 2. Received power level. 0 dB = mean received power. (a) City, antenna S6, v = 10 km/h, 24° satellite elevation. (b) Highway, antenna S6, v = 60 km/h, 24° satellite elevation.

statistical evaluation. Fig. 2(a) shows an example of the received signal power from a channel recorded in an area with narrow streets in the old city of Munich. The figure shows a high-frequency fading process which is superimposed on a low-frequency shadowing process. Relatively "good" and very "bad" channel periods can be distinguished having a mean level difference of approximately 15 dB. For instance, a crossroad permits an unobstructed "view" of the satellite from 928 to 932 s, while before and after this period the satellite is hidden by multistory flats. Fig. 2(b) shows the received signal power from a recording on a highway. For this case and for most of the time, only small level variations due to multipath fading predominate. At 684 s, total shadowing is caused by a bridge. Further shadowing events are caused by trees, etc.

In all recordings, the vehicle velocity v was kept constant to allow easy conversion between time, velocity, or distance. The distance of the fading events is determined by the stationary electromagnetic field and is independent of the mobile velocity. Since velocity = distance/time, the time duration of the fading events is inversely proportional to the velocity of the mobile terminal.

Fig. 3(a) shows the power spectral density of the fading signal amplitude for a short measurement period in a dense city environment. The power spectral density of the amplitude fading extends to 11 Hz and does not show a clear cutoff frequency. This was probably caused by variations in mobile speed and by signal components arriving from various elevations. In open areas, the power spectral density shows no peaking but decreases with frequency as shown in Fig. 3(b).

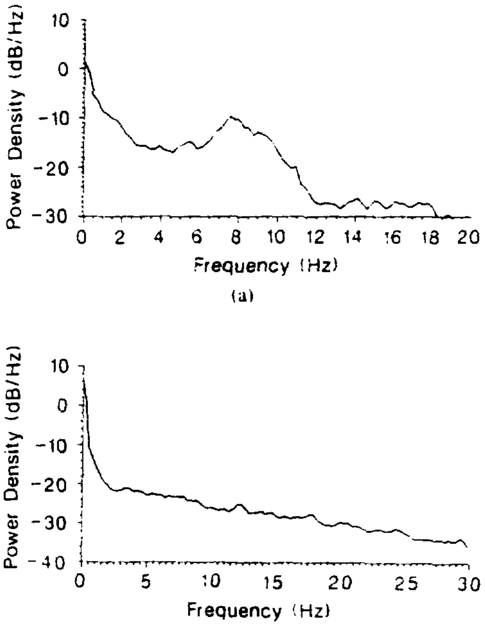


Fig. 3. Power spectral density of received signal amplitude. (a) City, antenna D5, elevation 24°, speed ca. 4 km/h. (b) Highway, antenna S6, elevation 24°, speed ca. 40 km/h.

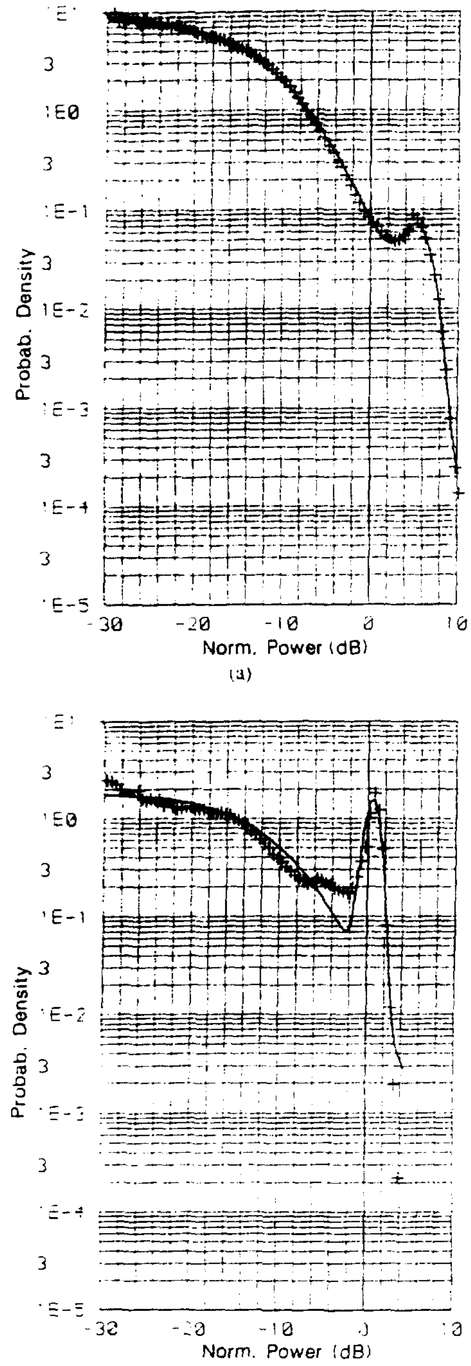


Fig. 4. Probability density function of received power. (a) City, antenna S6, 24° elevation, 0 dB = mean received power = link power − 5.2 dB. (b) Highway, antenna S6, 24° elevation, 0 dB = mean received power = link power − 0.6 dB.

Figs. 4(a) and 4(b) show the probability density function of the received signal power in a city environment and on a highway. The statistics of the recorded channel are designated as +. The full lines represent the channel model (5) with fitted parameters. The mean received power (0 dB) is related to the power of the unfaded satellite link through (6). The peaking of the density at high values of the received signal power is due to the reception of the direct satellite signal in unshadowed areas.

Figs. 5(a) and 5(b) show the cumulative probability distribution function of the received signal power in a city environment and on a highway. The statistics of the recorded channel are designated as +. The full lines approximating the measurements correspond to the channel model (5). The straight line represents a Rayleigh distribution. From Fig. 5(a) the received signal power is more than 10 dB below the unfaded satellite link with probability 0.60. On a highway, the corresponding probability is 0.085.

Time intervals with a received signal power level below a certain threshold are called fades. Let $p_f(\tau)$ be the probability density that a randomly chosen time instant lies within a fade of duration τ. Fig. 6 shows the probability

$$P_f(T_f) = \int_{T_f}^{\infty} p_f(\tau)\, d\tau \qquad (1)$$

of a time instant being in a fade with duration $\geq T_f$. For example, Fig. 6(a) shows that in a city environment fades below −10 dB relative to the average received signal power and longer than 0.1 s occur for 26% of time. The corresponding number on a highway is 6%, as shown in Fig. 6(b).

Time intervals with the received signal power level about a certain threshold are called connections. Fig. 7 shows the probability $P_c(T_c)$ of a time instant being in a connection of duration $\geq T_c$. Fig. 7(a) shows that in a city environment connections above −10 dB relative to the average received power and longer than 1 s occur for 34% of time. The corresponding number on a highway is 85%, as shown in Fig. 7(b).

In the next section, two types of models for the land mobile satellite channel are developed. The analog model attempts to reproduce the stochastic behavior of the received signal in amplitude and in phase. This model can be used for hardware or software simulation of the satellite link for

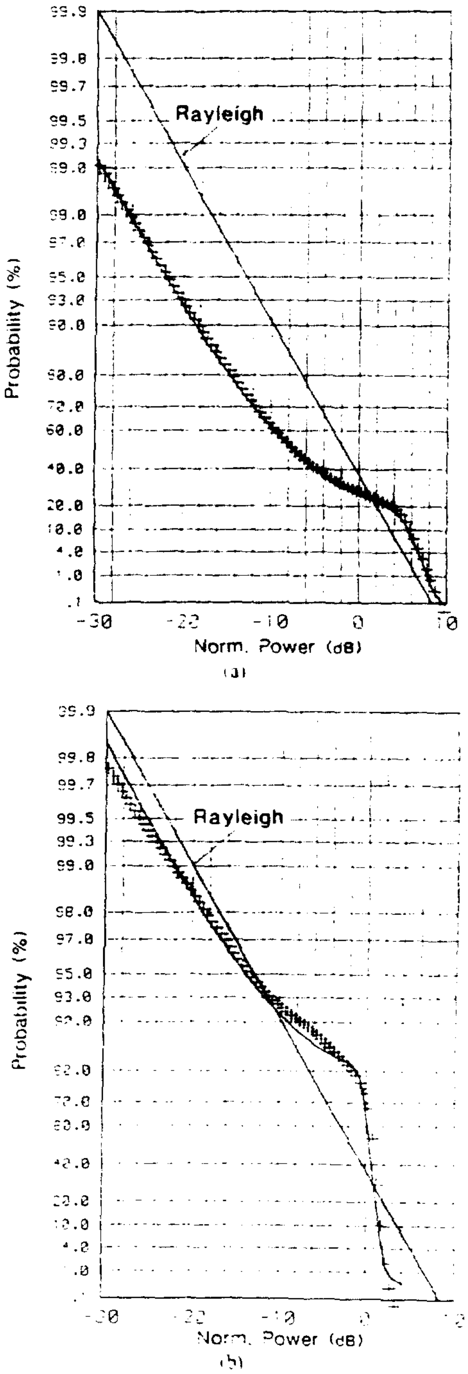


Fig. 5. Complementary cumulative probability distribution function of received power. (a) City, antenna S6, satellite elevation 24°, 0 dB = mean received power = link power −5.2 dB. (b) Highway, antenna S6, satellite elevation 24°, 0 dB = mean received power = link power −0.6 dB.

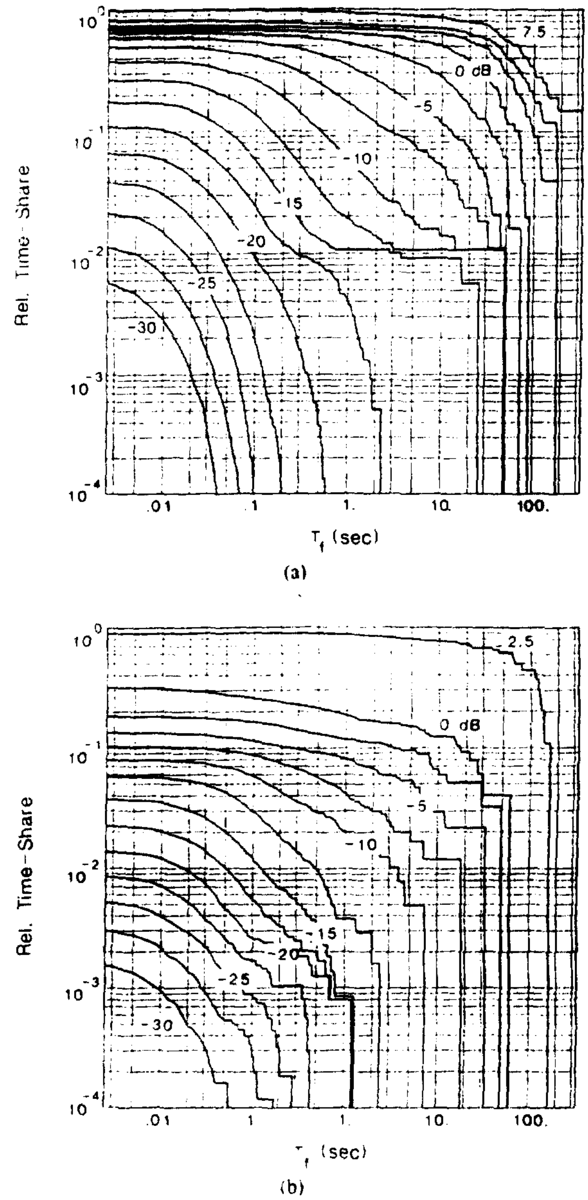


Fig. 6. Time-share of fades with duration $\geq T_f$. Parameter: threshold relative to mean received power. (a) City, antenna S6, satellite elevation 24°, v = 10 km/h. (b) Highway, antenna S6, satellite elevation 24°, v = 60 km/h.

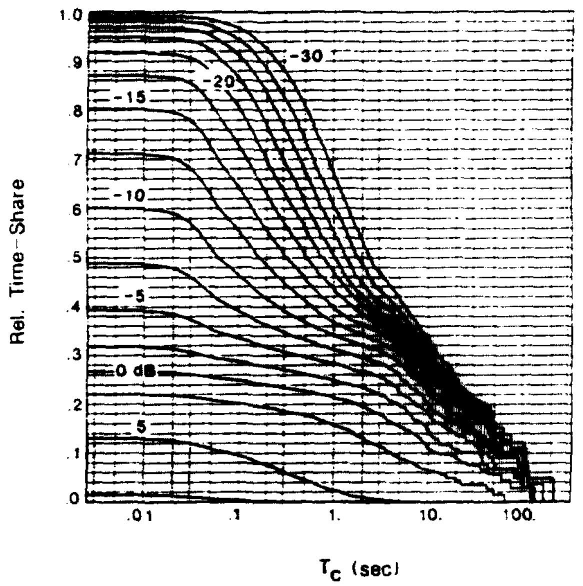
investigating modulation, coding, and accessing techniques. On the other hand, a digital channel model for reproducing stochastic bit error sequences has the advantage of better mathematical tractability. However, the parameters of the digital channel model depend on the signal-to-noise ratio of the satellite link and on the bit rate.

III. Models of the Land Mobile Satellite Channel

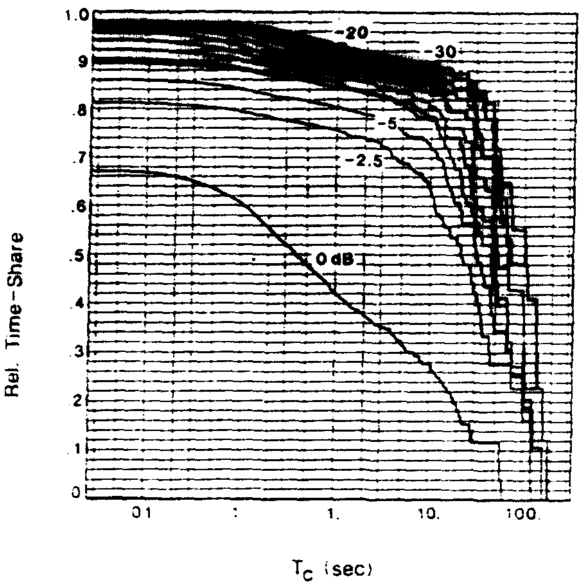
A. Modeling the Probability Density Function of the Received Signal Power

The development of an analog channel model is based on the physical phenomena of multipath fading and shadowing. A first step for this is an analytical approximation of the probability density function of the received signal power [15]. The mobile terminal is assumed as the receiver. However, the channel model is also valid when the mobile terminal is the transmitter.

As indicated by Figs. 2(a) and 2(b), it is useful to distinguish between time intervals with high received signal power ("good" channel state) and time intervals with low power level ("bad" channel state). The good channel state corresponds to areas with unobstructed "view" of the satellite (unshadowed areas), whereas the bad channel state represents areas where the direct satellite signal is shadowed by obstacles. In both of these cases, the satellite signal is reflected from a large number of objects in the surroundings of the mobile receiver. These signal components are received with independently time-varying amplitudes and phases: in the



(a)



(b)

Fig. 7. Time-share of connections with duration $\geq T_c$. Parameter: threshold relative to mean received power. (a) City, antenna S6, satellite elevation 24°, v = 10 km/h. (b) Highway, antenna S6, satellite elevation 24°, v = 60 km/h.

limit, these components add up to a complex Raleigh process. When no shadowing is present, this multipath signal is superimposed on the direct satellite signal, with the total received signal amplitude forming a Rician process. The momentary received power S obeys a Rician probability density:

$$p_{\mathrm{Rice}}(S) = c e^{-c(S+1)} I_0(2c\sqrt{S}). \tag{2}$$

Here c is the direct-to-multipath signal power ratio (Rice-factor) and I_0 is the modified Bessel function of order zero. The power of the unfaded satellite link is normalized to unity. Under the condition of no shadowing the mean received total power is $E\{S \mid \text{no shadowing}\} = 1 + 1/c$.

When shadowing is present, it is assumed that no direct signal path exists and that the multipath fading has a Rayleigh characteristic with short-term mean received power S_0. The probability density function of the received power conditioned on mean power S_0 is

$$p_{\mathrm{Rayl.}}(S \mid S_0) = \frac{1}{S_0} \exp(-S/S_0). \tag{3}$$

The slow shadowing process results in a time varying short-term mean received power S_0 for which a lognormal distribution is assumed:

$$p_{\mathrm{LN}}(S_0) = \frac{10}{\sqrt{2\pi}\,\sigma \ln 10} \cdot \frac{1}{S_0} \exp\left[-\frac{(10 \log S_0 - \mu)^2}{2\sigma^2}\right]. \tag{4}$$

Here μ is the mean power level decrease (in decibels) and σ^2 is the variance of the power level due to shadowing. With (3) and (4), the received power is described by a Rayleigh/lognormal distribution which is often used for the terrestrial land mobile channel [16].

In order to get the resulting probability density function of the received signal power, the densities (2)–(4) must be properly combined. To this end the time-share of shadowing, A is defined, and the resulting probability density function becomes

$$p(S) = (1 - A) \cdot p_{\mathrm{Rice}}(S) + A \cdot \int_0^\infty p_{\mathrm{Rayl.}}(S \mid S_0)\, p_{\mathrm{LN}}(S_0)\, dS_0 \tag{5}$$

where the integral expression results from the theorem of total probability. $p(S)$ is independent of vehicle velocity v which is assumed constant. In [17], a different approach suitable to foliage attenuation is described, assuming a lognormally distributed direct signal plus a Rayleigh distributed multipath signal with constant power.

The 0 dB value in Figs. 2 and 4–7 corresponds to the mean received power (the power of the unfaded link normalized to unity):

$$E\{S\} = (1 - A) \cdot \left(1 + \frac{1}{c}\right) + A \cdot 10^{(\ln 10 \cdot \sigma/10)^2/2 + \mu/10}. \tag{6}$$

For different satellite elevations, different types of environments, and different antennas, the parameters A, c, μ, and σ as given in Table II have been determined from the statistics of the recordings by a least square curve-fitting procedure. Table II is limited to city and highway environments which represent the worst and best case within the range of environments.

Using parameter values given in Table II, the probability